

Method for automatic compensation of a single-phase earth fault

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ABSTRACT

The paper demonstrates improving the reliability of power supply and operating safety of power receivers in electric networks of 6-10 kV, by controlling the neutral mode in extended electric networks of 6-10 kV with capacitive earth fault currents above 15 A. The purpose of the study is to increase the reliability of power supply and the safety of operation of power receivers in such electric networks, the establishment of patterns in controlling the neutral mode in extended 6-10 kV electric networks with capacitive earth fault currents above 15 A, as well as the development of a method and device automatic detection of single-phase earth fault current. Grounding methods and neutral modes in electric networks with a voltage of 6-10 kV are considered. The method and device for automatically determining the current of a single-phase earth fault were developed. In the result, the relationship between the active and inductive components of the neutral current during series RL grounding of the network $I_a/IL=(0.5\div 0.3)$ was established, which ensures reliable operation of the SPEF protection of both current and directional principles including the changes of capacity abruptly networks caused by switching outgoing lines.

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1. INTRODUCTION

In electric networks with a voltage of 6-10 kV, single-phase earth faults (SPEF) are the most common type of insulation damage (up to 80%). Due to the non-selective operation of serviceable protections from SPEF, a significant proportion (up to 50%) of alarms is observed, indicating that there is insulation damage that can lead to interphase faults during network operation. Reliable operation of relay protection equipment, increasing the security and uninterrupted power supply is largely determined by the neutral modes of electric networks. The regimes of “free” or grounded at most enterprises through an arcing reactor (ACR), neutrals of electric networks of 6-10 kV are not optimal, as they do not provide reliable protection against SPEF, often contribute to the appearance of overvoltages in the damaged and undamaged phase,

create conditions for the development of ferroresonant processes in the network [1], [2]. Recently introduced at many industrial associations high-resistance resistor neutral grounding allowed to solve many of these problems. Due to the application of active additional current at the fault location and the use of centralized current protection from single-phase earth faults, transverse selectivity of the action of these protections was achieved, overvoltages in the network were significantly reduced and the probability of ferroresonance processes was minimized.

However, high-resistance resistor grounding of a “free” neutral according to safety conditions, is only possible in electric networks of 6 kV with capacitive earth fault currents of up to 15 A [3]. Above this current, measures must be taken to compensate for capacitive current SPEF, which in practice usually amounts to connecting to the neutral of the ACR network on one of the fixed solders [4]. The latter circumstance can lead to the loss of operability of the protection against SPEF directional principle of operation (ZZP-1, RZN-3, etc.) with an abrupt change in the network capacity characteristic of electric networks (disconnecting outgoing feeders). In these networks, the majority (up to 12-15%) of the occurrence of single-phase insulation faults passes into the interphase ones through the earth, which is fraught with multiple injuries and a high risk of electric shock to the operating personnel [5], [6].

In the work of Zhang and others [1], taking into account the voltage drops in the network, an expression and the law of change in the injection current of the method of extinguishing the active voltage and the current of the fault point after extinguishing the active voltage are given. The authors note that when the transient resistance of the short circuit is large, the resistive voltage arc extinguishing technique can effectively compensate for the short-circuit point current to ensure reliable arc extinguishing. If the short-circuit resistance is relatively low, the load current is large, and the distance to the short-circuit is large, then active voltage extinction of the arc can lead to an increase in the fault current, even up to hundreds of amperes, which seriously reduces the arc extinction effect. Analysis of protection devices against SPEF [7] shows that the existing methods of protection against SPEF do not have sufficient reliability due to low selectivity, when disconnecting the damaged line of the protected network, one or several feeders are disconnected at the same time, where the phase insulation relative to the ground is not damaged, and configuration changes are not taken into account network during operation.

Thus, this paper proposes an improved resistive voltage arc suppression method that limits the phase voltage and short-circuit current during a low-resistance earth fault within a specific range to prevent an increase in the fault current. This method does not require measuring system parameters. Therefore, it can adapt to changes in the structure of the system, with the advantage of ease of use and improvement. The novelty of the presented research lies in the fact that a relationship was established between the active and inductive components of the neutral current with series grounding, which ensures reliable operation of the SPEF protection both in current and directional principles of action.

2. RESEARCH METHOD

One of the most key aspects of formal characterization of the digital devices synthesis is the choice of a language for describing the algorithms for their operation, which, along with the general requirements for algorithmic languages (completeness, consistency), must satisfy a number of special requirements [8]. The description of the functioning algorithms of the device under development in the selected language should be quite simple and convenient for practical use. In addition, the syntax of the language should allow for the existence of an efficient algorithm for transition from a job description in this language to a mathematical model of the synthesized device. From these points of view, the most acceptable language is the algorithmic flowgraph, which allows synthesizing automata close to minimal [9].

At the initial stage of the development of mathematical model of a digital device, a comprehensive flowgraph is constructed, in which logical conditions and micro-instructions are written in meaningful terms inside the conditional and operational vertices. As an algorithm for operation of the mathematical model in the developed device for automatic determination of the current of a single phase-to-earth fault protection in the electric network of 6-10 kV, an algorithm for automatic determination of the SPEF current in the 6-10 kV electric network was adopted, the comprehensive diagram of which is presented in Figure 1.

The synthesis of the Miles microprogram automaton according to the flowgraph of the algorithm [10] is carried out in the following order: 1) obtaining a marked algorithmic flowgraph; 2) construction of an automaton graph. To obtain a marked algorithmic flowgraph, the inputs of the vertices following the operational are marked with the symbols a_1, a_2, \dots according to the following rules: 1) symbol a_1 marks the entrance of the vertex following the initial one, as well as the entrance of the final vertex; 2) the inputs of all vertices following the operational must be marked; 3) the vertex entry is marked with only one symbol; 4) inputs of different vertices, except for the final one, are marked with different symbols.

Operators (microinstructions) Y_1, \dots, Y_T are written in the operational vertices of the algorithmic flowgraph. The initial flowgraph vertex is assigned the operator Y_0 , and the final one - Y_{T+1} . Each transition from the vertex $Y_i (i=0,1,\dots,T)$ to the vertex $Y_j (j=1,\dots,T+1)$ of the form $Y_i p_{i1} \dots p_{ir} Y_j$, passing through the conditional vertices p_{i1}, \dots, p_{ir} , corresponds to the conjunction:

$$a_{ij} = x_{ij}^{e_{i1}} \dots x_{ij}^{e_{ir}} \dots x_{ij}^{e_{iR}}, \quad (1)$$

where $x_{ij} \in X$ —logical condition written in the conditional vertex p_{ir} ; $e_{ij} \in \{0,1\}$ —symbol assigned to the output of the conditional vertex p_{ir} .

To go to the graph of the Miles automaton, each mark obtained at the first stage is associated with a vertex of the graph of the Miles automaton (a_1 is the initial state of the automaton). The graph of the Miles control microprogram automaton of the device for automatic determination of the SPEF protection current in the electric network of 6-10 kV is shown in the Figure 1.

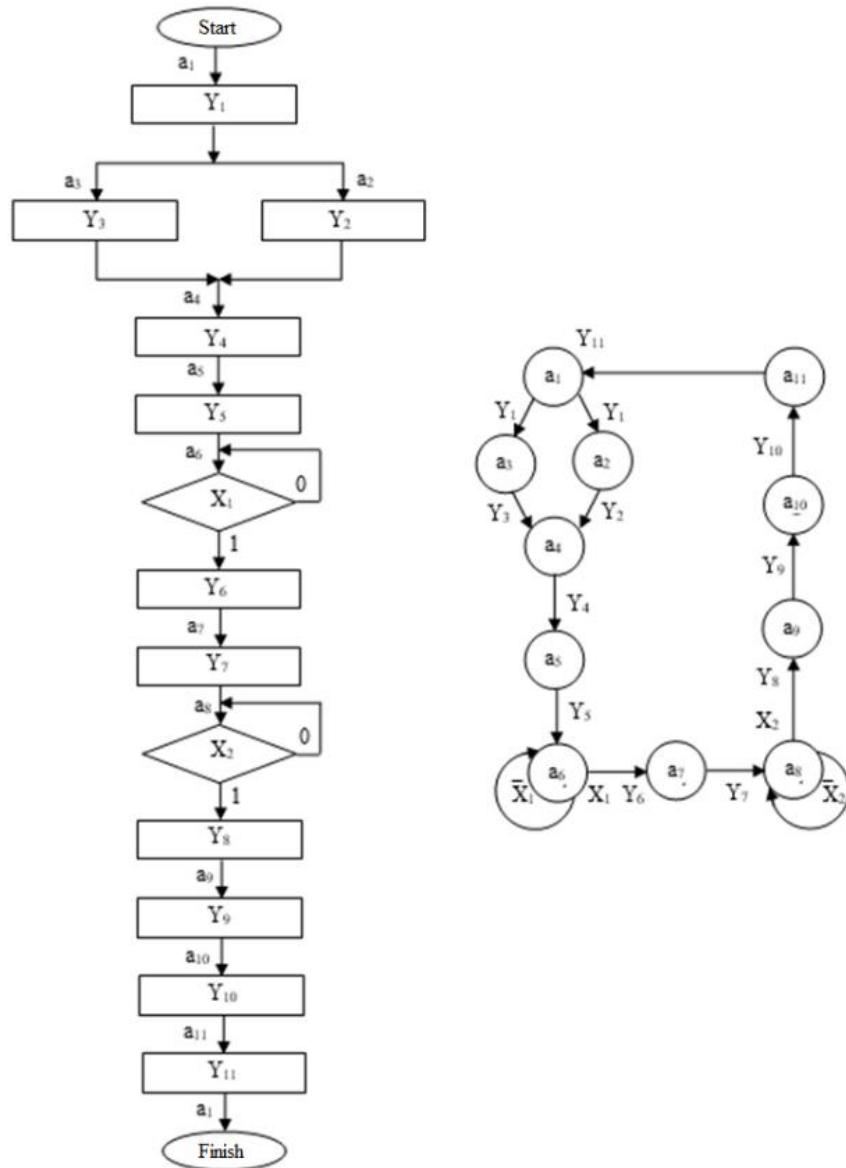


Figure 1. The marked graph is a diagram of the algorithm and a graph of the model of the control microprogram automaton Miles of the device for automatic determination of current SPEF in the electric network 6-10 Kv

The analysis of the algorithms for coding the states of the automata indicated their insignificant effect of minimizing the combinational circuit of the Miles control automaton of the device for automatic determination for the SPEF current in the electrical network of 6-10 kV. Therefore, sequential coding of the states of the automata in the format of a binary alphabet was carried out using the synchronization pulse of elementary memory automata. Thus, the following mathematical model were obtained as [11]:

– System of Boolean equations of functions for output signals:

$$\begin{aligned} Y_1 &= \bar{\tau}_1 \bar{\tau}_2 \bar{\tau}_3 \bar{\tau}_4; & Y_5 &= \bar{\tau}_1 \bar{\tau}_2 \bar{\tau}_3 \bar{\tau}_4 X_1; & Y_9 &= \tau_1 \bar{\tau}_2 \bar{\tau}_3 \bar{\tau}_4; \\ Y_2 &= \bar{\tau}_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4; & Y_6 &= \bar{\tau}_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4; & Y_{10} &= \tau_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4; \\ Y_3 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4; & Y_7 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4 X_2; & Y_{11} &= \tau_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4, \\ Y_4 &= \bar{\tau}_1 \tau_2 \tau_3 \tau_4; & Y_8 &= \bar{\tau}_1 \tau_2 \tau_3 \tau_4; \end{aligned} \quad (2)$$

– and system of Boolean equations for the excitation function of elementary memory automata

$$\begin{aligned} \phi_1 &= \bar{\tau}_1 \tau_2 \tau_3 \tau_4 X_2; \\ \phi_2 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \tau_4 \vee \tau_1 \bar{\tau}_2 \tau_3 \tau_4; \\ \phi_3 &= \bar{\tau}_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4 \vee \bar{\tau}_1 \tau_2 \bar{\tau}_3 \tau_4 \vee \tau_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4; \\ \phi_4 &= \bar{\tau}_1 \bar{\tau}_3 \bar{\tau}_4 \vee \bar{\tau}_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4 X_1 \vee \bar{\tau}_1 \tau_2 \tau_3 \bar{\tau}_4 \vee \tau_1 \bar{\tau}_2 \bar{\tau}_4 \end{aligned} \quad (3)$$

The synthesis of Moore microprogram automaton according to the flowgraph also consists in obtaining the marked algorithmic flowgraph and building the automaton graph. At the stage of obtaining the marked algorithmic flowgraph, the initial, final and operational vertices are marked with symbols a_1, \dots, a_m according to the following rules [9]: 1) the symbol a_1 marks the initial and final vertices; 2) different operational vertices are marked with different symbols; 3) all operational vertices must be marked [12]. The state marks are associated with the vertices of the Moore automaton graph [13]. To each transition path of the form $a_i x_{i1}^{e_{i1}} \dots x_{iR}^{e_{iR}} a_j$ the transition in the Moore automaton graph from the state a_i to the state a_j is associated. The case $R=0$ corresponds to the transition in the Moore automaton graph under the influence of the input signal $x(a_i, a_j) = 1$.

The mathematical model of Moore automatic device was obtained as the following systems:

– the system of Boolean equations of the output function:

$$\begin{aligned} Y_1 &= \bar{\tau}_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4; & Y_5 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4; & Y_9 &= \tau_1 \bar{\tau}_2 \bar{\tau}_3 \bar{\tau}_4; \\ Y_2 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4; & Y_6 &= \bar{\tau}_1 \tau_2 \bar{\tau}_3 \tau_4; & Y_{10} &= \tau_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4; \\ Y_3 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4; & Y_7 &= \bar{\tau}_1 \tau_2 \tau_3 \bar{\tau}_4 X_2; & Y_{11} &= \tau_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4, \\ Y_4 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \tau_4; & Y_8 &= \bar{\tau}_1 \tau_2 \tau_3 \tau_4; \end{aligned} \quad (4)$$

– a system of Boolean equations for the excitation functions of elementary memory automata:

$$\begin{aligned} \phi_1 &= \bar{\tau}_1 \tau_2 \tau_3 \tau_4 X_2; \\ \phi_2 &= \bar{\tau}_1 \bar{\tau}_2 \tau_3 \tau_4 \vee \tau_1 \bar{\tau}_2 \tau_3 \tau_4; \\ \phi_3 &= \bar{\tau}_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4 \vee \bar{\tau}_1 \tau_2 \bar{\tau}_3 \tau_4 \vee \tau_1 \bar{\tau}_2 \bar{\tau}_3 \tau_4; \\ \phi_4 &= \bar{\tau}_1 \bar{\tau}_3 \bar{\tau}_4 \vee \bar{\tau}_1 \bar{\tau}_2 \tau_3 \bar{\tau}_4 X_1 \vee \bar{\tau}_1 \tau_2 \tau_3 \bar{\tau}_4 \vee \tau_1 \bar{\tau}_2 \bar{\tau}_4. \end{aligned} \quad (5)$$

The marked flowgraph of the algorithm and the graph of the Moore control machine model of the device for automatic determination of the SPEF current in the electrical network of 6-10 kV are shown in Figure 2. In the circuit diagram of the parallel neutral grounding device R-L, there is always a zero-resistor stage put into operation, which does not allow the neutral of the network to be switched to the “dead” grounding mode [14]. In operating practice, there is a damage to the insulation of any phase relative to the ground, leading to the emergence of SPEF. Known methods for determining the current SPEF have not found wide application, since they have a drawback: the involvement of personnel for the visual removal of voltage modules and currents necessary to calculate the value of the current SPEF. Therefore, in order to increase the level of electrical safety and automation of elements of the power supply system of enterprises, it is necessary to develop a means of automatically detecting SPEF current in 6-10 kV networks, the main advantages of which are the automatic detection and accumulation of the dynamics of changes in SPEF current over time [1], [15], [16].

The most optimal of the existing neutral modes at the enterprises in networks of 6-10 kV with capacitive currents of SPEF less than 15A should be recognized as “RV-network”. The transition of SPEF to double through the ground poses another important task of protection against such damage, especially in extended networks, where even the currents of the “dead” metal circuit between the phases of the network

may be lower than the normal starting currents of the electric motors of the drive machines and complexes. This situation is especially dangerous in case of arcing, alternating double earth faults, since in the places of damage a large amount of thermal energy is released, which could result in cable fire, serious damage to the insulation of the motor windings, etc. [17], [18].

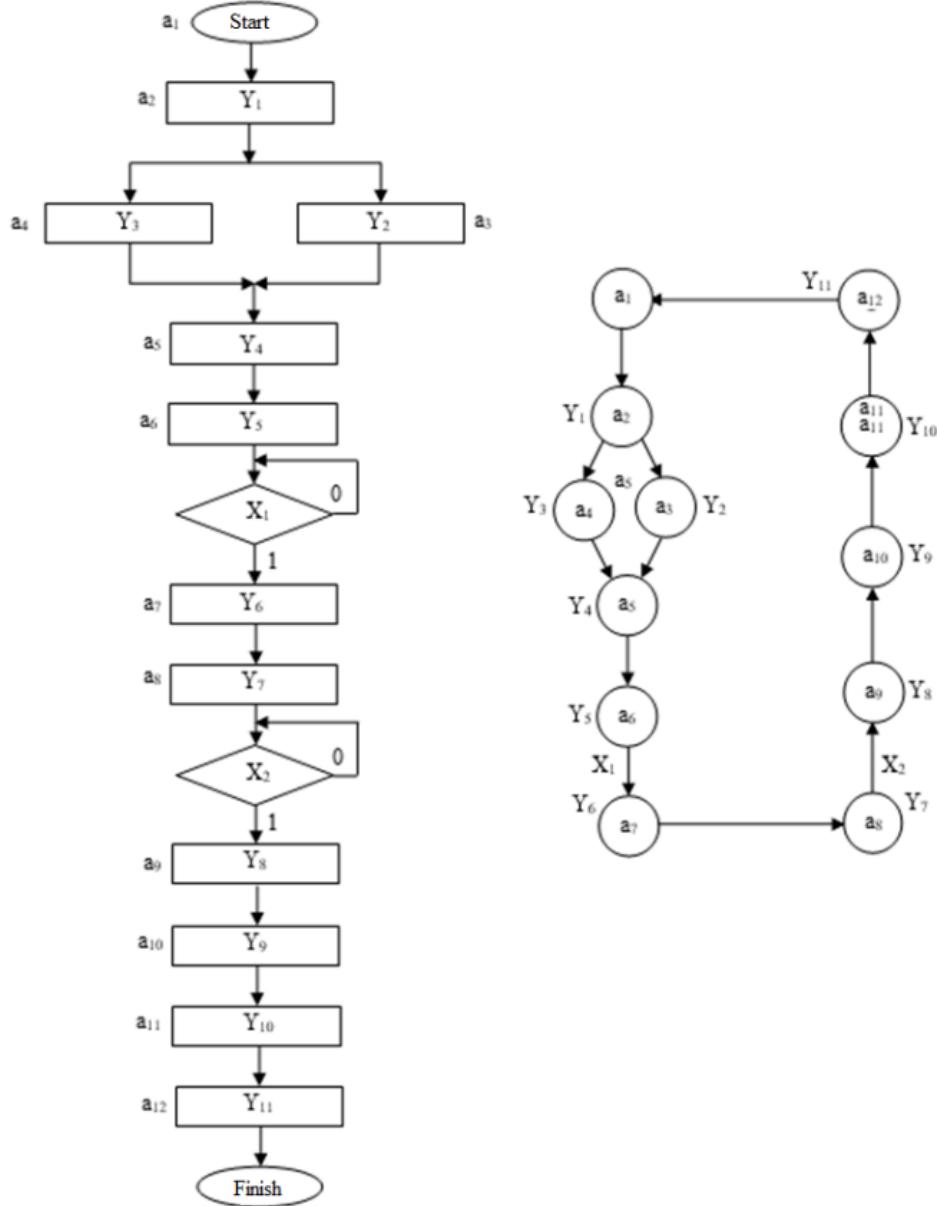


Figure 2. The marked graph-diagram and graph of the control firmware of the Moore automatic device for detecting SPEF current in the electric network 6-10 kV

3. RESULTS AND DISCUSSION

The paper presents a methodology for the study and selection of optimal parameters of active-inductive resistance in neutral. As options for circuit solutions to ensure reliable and selective operation of SPEF protections, the minimum level of overvoltage during arc faults and electrical safety when touching grounded equipment, the following are proposed: parallel connection of the neutral resistor and ACR; series connection of resistor modules and ACR [19].

The main structural elements of the developed method for automatically determining the current of a single-phase earth fault in an electric network of 6-10 kV are: the architecture of the device that implements the developed method, which determines and justifies its main functional blocks and functional diagram;

algorithm for automatically detecting SPEF current in an electric network of 6-10 kV, which determines the sequence of actions. The developed architecture is based on the backbone-modular principle of organizing microprocessor devices and systems and allows you to minimize the amount of device software due to the fact that the operation of analog-to-digital conversion and counting of time intervals in hardware by introducing the appropriate blocks. The functional diagram of the device under development is shown in Figure 3. To achieve greater information content and visualization of the display, the microprocessor units of the device are interconnected with each other through a common trunk that combines a data bus, address bus and control bus.

According to the results of the analysis of methods for determining the current of a single-phase earth fault as a prototype, an indirect method for determining the current of a single-phase earth fault in an electric network with an isolated neutral voltage above 1000 V is adopted as a prototype for developing an algorithm for automatically detecting the SPEF current in the electric network of 6-10 kV practical application. The method is based on the measurement of linear voltage modules, phase voltage relative to earth, zero sequence voltage after connecting one of the phases of the electric network and the earth with additional capacitive conductivity. The main advantage of this method compared to other similar indirect methods for determining the SPEF current is the significant simplicity of measuring the phase voltage modules with respect to ground, line voltage, zero sequence voltage and calculating the SPEF current value based on the measured data at high accuracy of the determined SPEF current [20]-[22].

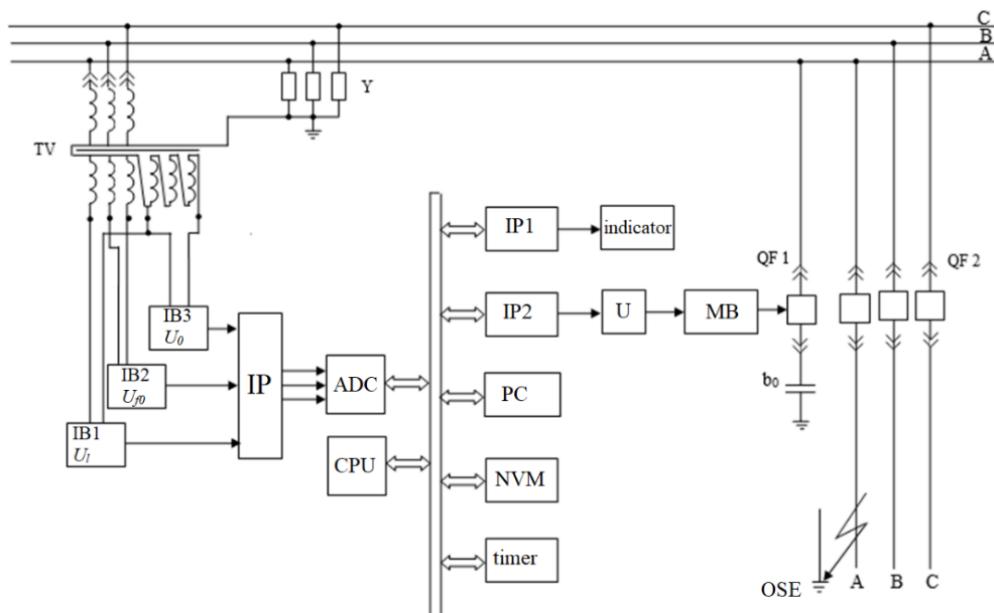


Figure 3. Functional diagram of a device for automatically detecting current SPEF in an electric network of 6-10 kV

An analysis of the methods for the mathematical determination of digital computers has shown that the most effective are the methods of the theory of automata, which make it possible to synthesize rather complex models of computing devices for determining applied problems. Also, in the process of mathematical determination of the SPEF current in an electric network of 6-10 kV, elements of Boolean algebra, graph theory and algorithms are used. The developed mathematical model allows automatic determination of the current of a single-phase earth fault in an electric network with a voltage of 6-10 kV as shown in Figure 1. The main task of the Miles microprogram machine is to develop time-distributed sequences of control signals, under the influence of which some operations are carried out in the operational machine [23]. A model has been developed for the Moore control microprogram automaton for a device for automatically determining the current of a single-phase earth fault in an electric network of 6-10 kV.

The marked graph-diagram of the algorithm and the graph of the model of the Moore control firmware automatic devices for automatically detecting the SPEF current in the electric network of 6-10 kV are presented in Figure 4. In scientific work, a device was developed for automatic determination of the current of a single-phase earth fault in an electric network of 6-10 kV. The development of a device for

automatically determining the current of a single-phase earth fault in an electric network of 6-10 kV consists in the selection and justification of the element base for the technical implementation of its architecture. The main requirements for the control units of information processing devices, which include the SPEF automatic current detection device in the 6-10 kV electric network, are: low cost, high reliability, high miniaturization, low power consumption, operability in harsh operating conditions, sufficient performance to perform the required functions, versatility. These requirements can be met by a device for automatically determining the current of a single-phase earth fault in an electric network of 6-10 kV based on a microcontroller control system.

The functional diagram of the SPEF automatic current sensing device in a 6-10 kV electric network is shown in Figure 4 and contains: a three-phase electric network with phases A, B and C; TV-voltage transformer; full conductivity of the electric network-Y; additional capacitive conductivity- b_0 ; load switch (QF 1), switching additional capacitive conductivity; load switch (QF 2), switching power supply to power consumers; microcontroller (MCU); BVS-block of voltage sensors; analog-to-digital converter (ADC) timer; non-volatile random access memory (NVRAM); MB-measuring body; power supply unit (PSU); CKB-control key block; GIU-galvanic isolation unit.

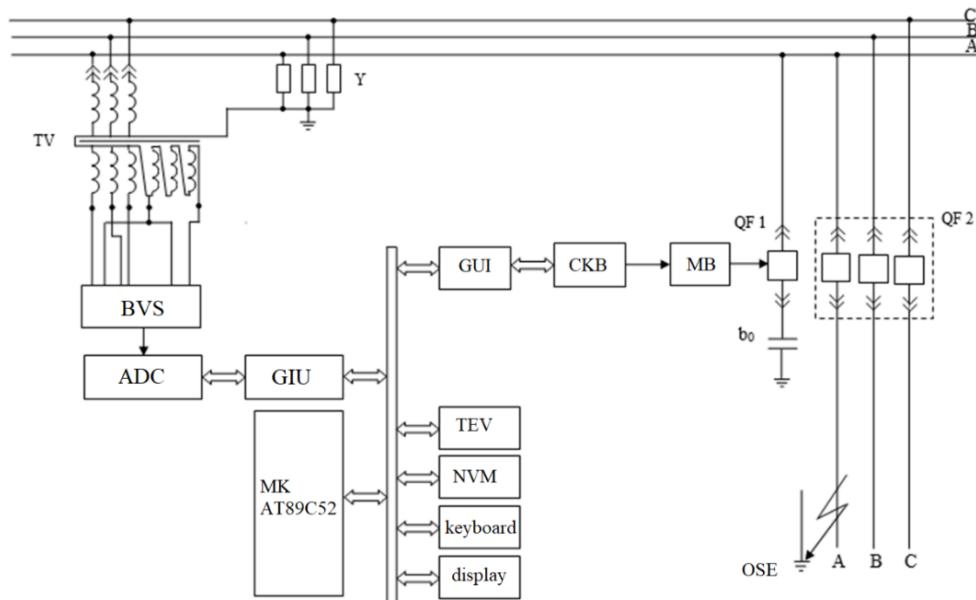


Figure 4. Functional diagram of the device for automatic determination of current SPEF in the electric network 6-10 kV, implemented on the ISSU

An in-service software upgrade (ISSU) [24] is equipped with a 10 W switching power supply and is housed in a sealed metal case with dimensions of 300×320×40 mm and degree of protection IP64. This provides a sufficiently reliable protection of the control system from adverse operating conditions, such as mechanical damage, dust, moisture and external electromagnetic interference, and is equipped with a heater with an electronic thermostat, which ensures an operating temperature range of $\pm 50^{\circ}\text{C}$ [25].

4. CONCLUSION

Thus, the relationship between the active and inductive components of the neutral current during series RL grounding of the network $I_a/IL=(0.5\div 0.3)$ was established, which ensures reliable operation of the SPEF protection of both current and directional principles of operation, including when the capacitance changes abruptly networks caused by switching outgoing lines.

The results of testing the proposed methods for protection relays showed that, in comparison with other similar indirect methods for determining the current, the SPEF method is distinguished by a significant simplicity of measuring the modules of the phase-to-earth voltage, line voltage, residual voltage and calculating the SPEF current value based on the measured data with high accuracy of the determined current

SPEF. The developed mathematical models makes it possible to automatically determine the current of a single-phase earth fault in an electric network with a voltage of 6-10 kV.

The advantages of a device for automatic detection of single-phase earth fault current in a 6-10 kV electrical network based on a microcontroller control system are: low cost, high reliability, high degree of miniaturization, low power consumption, operability in harsh operating conditions, sufficient performance to perform the required functions, universality. The developed algorithm for the automatic determination of the single-phase earth fault current in the 6-10 kV electrical network is based on the indirect method for determining the SPEF current parameters in the electrical network with an isolated neutral voltage above 1000 V. When implementing the results of the work, the effect will be expressed in a 30-40% reduction in unjustified downtime of technological equipment due to the non-selective action of the main types of relay protection and overvoltage in the network during intermittent arc faults to earth.

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